Anatomic Variation of Structural Properties of Periacetabular Bone as a Function of Age

A Quantitative Computed Tomography Study

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Abstract: The shape of the acetabulum, the volume of the periacetabular bone, and its density for 125 patients with a wide age range have been quantified using quantitative computed tomography. The goals were to study the relationship between geometric and densitometric properties and provide normative data for finite-element analysis. Significant correlations were found between acetabular diameter and (1) depth, (2) cancellous periacetabular bone density, and (3) periacetabular total bone volume. Only changes in densitometric properties significantly correlated with age. Sphericity of the acetabulum did not increase with age. Variability in bone morphology and density was found for both male and female groups. Surgeons using purely geometric measures to quantify the integrity of acetabular bone should be aware of their limitations when selecting hardware for total hip arthroplasty. Key words: acetabulum, morphology, bone density, age factors, structure, finite-element analysis.

Finite-element analysis (FEA) is commonly used to gain a better understanding of the biomechanics for the normal and reconstructed hip [1–12]. Computation of the stresses in the periacetabular bone requires knowledge of the material properties and geometry. Data on the mechanical properties of the periacetabular bone are scarce. Approximate models have been used in the absence of more complete information—for example, assuming that the acetabulum is hemispheric or that the periacetabular bone is isotropic and of constant density in different regions of the periacetabulum. A detailed summary on material property assumptions for hip bone has been provided by Dalstra et al. [13]. Several investigators have used computed tomography (CT) to measure bone geometry and density [14–21]. Computed tomography can be used in FEA to develop element meshes and validate models [6,20,22]. Quantitative CT (QCT)—derived properties for bone have become the gold standard of theoretic comparison for three-dimensional FEA of bone–prosthesis systems [22]. Formulas for the relationship between elastic modulus and apparent density have been derived for the femur by Carter [23] but have not been determined for the periacetabular bone. The observation that the outcome of hip arthroplasty is dependent on the quality and morphology of periacetabular bone, especially in revision cases [24–26] has led to attempts to quantify anatomic variation of the structural properties.
There is a limited amount of information regarding structural properties of periacetabular bone as they relate to total hip arthroplasty due to the complexity of the morphology, complexity of mechanical testing, and absence of a three-dimensional radiographic longitudinal database for the hip. Primarily, the focus has been on the femur [27,28]. In previous studies, the morphology of the pelvis has been quantified to fit iliopubic bar pins [29], determine sexual dimorphism [30,31], and characterize pathologic deformity [32]. The mechanical properties for pelvic trabecular bone have been reported for a limited number and age range of subjects [13]. To characterize geometric and densitometric relationships, we quantified the dimensions and sphericity of the acetabulum and investigated the value of these acetabular geometric measures in predicting periacetabular bone density and cancellous and cortical bone quantity. Factors for subject sex and age were accounted for to define a normal hip socket.

Materials and Methods

A retrospective study comprising a total of 125 hip CT examinations from January 1995 until July 1995 was carried out in patients (58 men, 67 women) who were imaged for abdominal pain. Patients with severe acetabular bone deficiencies or abnormal acetabular morphology were excluded. Patients were selected by age to create a uniform sample from each decade of life (mean age, 52.9 years; SD, 19.5 years; range, 10–97 years).

Transaxial QCT examination of the pelvis was performed with a CT scanner (Siemens Somatom Plus, Iselin, NJ) with 8- or 10-mm slice collimation at 10-mm intervals through the pelvis. Scan parameters were 3.2 seconds, 315 mAs, and 125 kVp. The mean pixel size was 0.75 mm (SD, 0.15 mm; range, 0.54–1.78 mm). Imaging was performed from the superior aspect of the anterosuperior iliac spine to the inferior aspect of the obturator foramen (12 ± 1 transaxial sections = 2 × acetabular diameter), as shown in Fig. 2. Histogram methods could not be used to establish bone thresholds because of the percentage of cancellous bone pixels [22], so thresholds were estimated from review of the anatomy so that CT numbers were within the ranges 100–500 HU for cancellous bone and 501–1,700 HU for cortical bone. Outer boundaries for the periacetabular bone (Fig. 2) were detected using a modified Rosenfeld algorithm [22]. Boundary editing was necessary in the vicinity of the femoral head and pubic symphysis. Discrete integrals [36] were calculated for cancellous, cortical, and total bone volume with the average density of the tissues. For example, the cancellous bone volume (Vcanc) was calculated as

\[
V_{\text{canc}} = \sum_{i=1}^{4} \sum_{j=1}^{ROI\,\text{pixels}} dA_{ij} t_i,
\]

where \(A\) = pixel area, \(t\) = scan thickness, and ROI = region of interest.

Anthropometric analysis was performed by 2 examiners using a multiplanar volume reconstruction (MPR) program [35] on a computer workstation (Indigo II, Silicon Graphics, Mountain View, CA). Image data were analyzed as 512 × 512-pixel images with full 16-bit precision. Periacetabular bone was quantified from the anterosuperior iliac spine to the inferior aspect of the obturator foramen (12 ± 1 transaxial sections 2 × acetabular diameter), as shown in Fig. 2. Histogram methods could not be used to establish bone thresholds because of the percentage of cancellous bone pixels [22], so thresholds were estimated from review of the anatomy so that CT numbers were within the ranges 100–500 HU for cancellous bone and 501–1,700 HU for cortical bone. Outer boundaries for the periacetabular bone (Fig. 2) were detected using a modified Rosenfeld algorithm [22]. Boundary editing was necessary in the vicinity of the femoral head and pubic symphysis. Discrete integrals [36] were calculated for cancellous, cortical, and total bone volume with the average density of the tissues. For example, the cancellous bone volume (Vcanc) was calculated as

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The maximum diameter and depth of the acetabulum were measured by identifying acetabular anatomic landmarks (Fig. 2). Coronal, sagittal, and transaxial planar information was used to identify
peak acetabular diameter and depth. The departure from sphericity was quantified using the same measurements as Bullough et al. [37]. In this case, the radius of the acetabulum was measured at 4 points equidistant from one another along an equatorial circle in a transaxial plane. By dividing the difference between the maximum and minimum radii by the mean radius, the departure from sphericity was quantified.

A statistical analysis was carried out on these data using linear regression correlation analysis (with 95% confidence limits) as grouped by sex and age to identify the mean, range, standard deviation, and correlation of the measurement values (StatView, Abacus Concepts, Berkeley, CA).

**Results**

There was moderate variation in acetabular geometry: male mean diameter, 52.6 ± 3.6 mm (range, 42.7–60.2 mm); female mean diameter, 46.7 ± 3.9 mm (range, 39.9–60.7 mm); male mean depth, 23.8 ± 2.7 mm (range, 17.7–29.8 mm); female mean depth, 21.8 ± 2.8 mm (range, 17.5–30.7 mm) (Figs. 3, 4). On average, male acetabular dimensions were 10% larger than female dimensions. Significant moderate correlations existed for both sexes between the acetabular diameter and depth (men: \( r = .52, P = .001 \); women: \( r = .24, P = .05 \)). In addition, the acetabular diameter did not correlate well with the acetabular depth within individual subjects as shown in Figure 5. The high variation of acetabular depth for a specified size diameter within individuals is illustrated in Figure 5. Poor correlation was found between sphericity of the acetabulum and age of the subject (\( r = .05, P = .604 \)).

The moderate correlation between acetabular diameter and total bone volume of the periacetabular bone stock was similar for males (\( r = .42, P = .001 \)) and females (\( r = .46, P = .0001 \)) (Fig. 6). The cancellous and cortical total bone volumes each were 19% less for women than for men. Both
men and women had three times as much cancellous bone volume as cortical on average. The mean cancellous bone density decreased for men ($r = .56$, $P = .0001$) and more significantly for women ($r = .62$, $P = .0001$) as a function of age as shown in Figure 7. Variations in the apparent density for both cancellous and cortical bone were similar in distribution and of comparable magnitude for both sexes (Table 1).

Linear regressions are presented for each of the study design variables corresponding to density and geometry for men and women (Tables 2, and 3). The weakest correlations for men were between diameter and both cancellous and cortical percentage, in addition to depth and average cortical density. The weakest correlations for women were between diameter and cancellous percentage, age and total volume, and cancellous percentage and total volume. These findings support the intuition that geometric parameters would not necessarily correlate with age.

**Discussion**

The reported degree of variation in acetabular dimensions is significant and should be considered when assuming the acetabulum is spherical. The reported degree of sphericity of the acetabulum has varied from nearly spherical with deviations of less than 500 $\mu$m [37] to fairly aspherical [37]. Our findings agree with those of Bullough et al. in that the acetabulum is aspherical with a tendency to be more shallow than deep by as much as 20% of the depth. Contradicting hypotheses exist claiming that the acetabulum is increasingly spherical with age [37] and is not increasingly spherical with age [38]. Our findings agree with those of Kim [38]. This nonsphericity of the acetabulum will affect the congruency of the hip joint, potentially making it depend on the position of the joint.

Dalstra et al. quantified trabecular bone densities throughout the pelvic bone [13]. The average val-
Fig. 6. Variation in total periacetabular bone volume plotted with respect to the acetabular diameter. For both men and women, there is a statistically significant linear correlation between the amount of bone and the diameter of the acetabulum. There can be a high degree of anatomic variation in the amount of bone stock for a specific acetabular diameter. For example, a female 87-year-old acetabulum with a 52.6-mm diameter has a corresponding bone stock of 136.8 cm³. A female 60-year-old acetabulum with a 51.3-mm diameter has a corresponding bone stock of 279.9 cm³ (205%).

Fig. 7. Variation in mean cancellous bone density plotted with respect to age. For women, there is a statistically significant linear correlation between the mean density and age. There is a high degree of anatomic variation in the average densitometric properties.

Table 1. Densitometric Properties* for Male and Female Periacetabular Bone

<table>
<thead>
<tr>
<th></th>
<th>Periacetabular Cancellous Bone</th>
<th>Periacetabular Cortical Bone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male bone</td>
<td>1.196 ± 0.192 (1.153–1.238)</td>
<td>1.506 ± 0.027 (1.442–1.572)</td>
</tr>
<tr>
<td>Female bone</td>
<td>1.197 ± 0.172 (1.156–1.242)</td>
<td>1.509 ± 0.033 (1.405–1.570)</td>
</tr>
</tbody>
</table>

* The data are presented as means ± SD and data range of the mean values for each subject in the population; that is, the value is the mean of the means.
Table 2. Linear Correlations* Obtained From Male Acetabular Geometry and Periacetabular Bone Stock

<table>
<thead>
<tr>
<th></th>
<th>Periacetabular Cancellous Bone</th>
<th>Periacetabular Cortical Bone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Volume</td>
<td>Percent†</td>
</tr>
<tr>
<td>Age</td>
<td>0.1, 0.48 0.08, 0.57 0.28, 0.03 0.56, 0.0001</td>
<td>0.3, 0.02 0.28, 0.03 0.12, 0.39 0.21, 0.12</td>
</tr>
<tr>
<td>Diameter</td>
<td>0.52, 0.001 0.42, 0.001 0.02, 0.9 0.08, 0.55</td>
<td>0.23, 0.08 0.09, 0.51 0.06, 0.65 0.41, 0.0001</td>
</tr>
<tr>
<td>Depth</td>
<td>0.39, 0.003 0.09, 0.51 0.23, 0.09</td>
<td>0.23, 0.08 0.09, 0.51 0.06, 0.65 0.41, 0.0001</td>
</tr>
<tr>
<td>Cancellous bone</td>
<td>Volume</td>
<td>0.19, 0.15 0.001, 0.99</td>
</tr>
<tr>
<td>Percent</td>
<td>0.73, 0.0001</td>
<td>0.9, 0.0001</td>
</tr>
<tr>
<td>ρ</td>
<td>0.10, 0.41 0.14, 0.27 0.19, 0.12</td>
<td>0.09, 0.51 0.24, 0.05 0.15, 0.22 0.08, 0.50</td>
</tr>
<tr>
<td>Cortical bone</td>
<td>Volume</td>
<td>0.22, 0.08 0.24, 0.05</td>
</tr>
<tr>
<td>Percent</td>
<td>0.75, 0.001</td>
<td>0.73, 0.0001</td>
</tr>
<tr>
<td>ρ</td>
<td>0.5, 0.0001 0.75, 0.0001 0.67, 0.0001</td>
<td>0.5, 0.0001 0.75, 0.0001 0.67, 0.0001</td>
</tr>
</tbody>
</table>

* The data are presented as the coefficient of linear correlation r, and analysis of variance F-test P. NA, not applicable; that is, cancellous percent and cortical percent would sum to 100%. † Percent of total periacetabular bone that is cancellous. ‡ Values for mean apparent density of cancellous periacetabular bone stock.

selecting the prosthesis may be needed. Load transfer from the prosthesis to the bone tissue depends on the material stiffness and quantity of bone stock [11]. Theoretic biomechanical analysis is needed to establish the relationship between this high degree of anatomic variation and the resultant effect on load transfer as it relates to mechanical stability of the prosthesis. When adjunctive fixation methods are used for the prosthesis, the integrity of the supporting bone stock is critical in the success of these fixation features. A clinical follow-up investigation of prosthetic failure rates, with correlation for integrity of supporting bone stock, may be very illuminating.

Study limitations include geometric errors in the measurement values, which may be introduced by (1) the sampling size used for the data, (2) the accuracy of the plane orientation used for analysis, and (3) the use of subjective bone thresholds. Similar to Dalstra and colleagues' study [13], a scan spacing and thickness of 10 x 8 mm was used to image the acetabulum. The use of dual-energy CT or helical CT could improve the sampling size and make the three-dimensional reconstruction more accurate; however, this imaging capability was not available for the retrospective data. Various types of artifacts can degrade CT image accuracy including beam scatter, hardening, and partial volume averaging. The threshold at which a CT image is segmented is an important factor in the accuracy of measuring bone properties [40]. Geometric errors in the cortical boundary outer diameter have been reported on the order of 5% [40,41]. The use of a phantom minimized these errors. A longitudinal database would be more scientifically precise for deriving densitometric and geometric relationships.

Table 3. Linear Correlations* Obtained From Female Acetabular Geometry and Periacetabular Bone Stock

<table>
<thead>
<tr>
<th></th>
<th>Periacetabular Cancellous Bone</th>
<th>Periacetabular Cortical Bone</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Volume</td>
<td>Percent†</td>
</tr>
<tr>
<td>Age</td>
<td>0.21, 0.08 0.24, 0.05 0.39, 0.001 0.62, 0.0001</td>
<td>0.28, 0.02 0.39, 0.001 0.27, 0.03 0.004, 0.97</td>
</tr>
<tr>
<td>Diameter</td>
<td>0.19, 0.12 0.65, 0.0001 0.08, 0.50 0.24, 0.05</td>
<td>0.28, 0.02 0.08, 0.50 0.18, 0.15 0.46, 0.0001</td>
</tr>
<tr>
<td>Depth</td>
<td>0.24, 0.05 0.14, 0.27 0.19, 0.12</td>
<td>0.08, 0.5 0.14, 0.27 0.3, 0.01 0.38, 0.002</td>
</tr>
<tr>
<td>Cancellous bone</td>
<td>Volume</td>
<td>0.22, 0.08 0.24, 0.05</td>
</tr>
<tr>
<td>Percent</td>
<td>0.75, 0.001</td>
<td>0.75, 0.0001</td>
</tr>
<tr>
<td>ρ</td>
<td>0.5, 0.0001 0.75, 0.0001 0.67, 0.0001</td>
<td>0.5, 0.0001 0.75, 0.0001 0.67, 0.0001</td>
</tr>
<tr>
<td>Cortical bone</td>
<td>Volume</td>
<td>0.78, 0.0001 0.47, 0.0001 0.58, 0.0001</td>
</tr>
<tr>
<td>Percent</td>
<td>0.71, 0.0001</td>
<td>0.71, 0.0001</td>
</tr>
<tr>
<td>ρ</td>
<td>0.04, 0.872</td>
<td>0.04, 0.872</td>
</tr>
</tbody>
</table>

* The data are presented as the coefficient of linear correlation r, and analysis of variance F-test P. NA, not applicable; that is, cancellous percent and cortical percent would sum to 100%. † Percent of total periacetabular bone that is cancellous. ‡ Values for mean apparent density of cancellous periacetabular bone stock.
as a function of age; however, factors for radiation exposure and time restrictions make it not feasible at this time.

**Conclusion**

The periacetabular bone demonstrates a strong degree of geometric and densitometric variation from subject to subject primarily as a function of age and secondarily as a function of sex. When modeling the structural properties of the pelvis, the age-dependent qualities of the periacetabular bone should be accounted for. The values presented in these data will make this possible. With respect to fitting acetabular cups, a purely geometric approach may be less than optimal given the densitometric and volumetric property variation for the patient population. The engineering relationship between apparent density and material properties needs to be studied. Quantitative CT-derived measurements and efficacy of acetabular prostheses needs to be studied. Quantitative CT-derived FEA has reached a high degree of maturity for the femur. Future work lies in quantifying the relationship between apparent density and material parameters like elastic modulus and ultimate strength for the acetabulum, so that a more accurate assessment of periacetabular bone stress can be completed.

**References**

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